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Low polarisation dependence (< 0.3dB) in an EA modulator using a polyimide-buried high-mesa ridge structure with an InGaAsP bulk absorption layer

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Indexing terms: Electroabsorption modulators

The electroabsorption modulator combining a polyimide-buried high-mesa ridge structure with an InGaAsP bulk absorption layer which the authors have developed demonstrates an extremely low polarisation-dependent loss of less than 0.3dB with a practical and sufficient attenuation of 20dB.

Introduction: A high-speed electroabsorption (EA) modulator is a very attractive device both in multigigabit long-haul lightwave transmission systems and in optical soliton transmission systems for stabilising the generation of $sech^2$-like optical pulse trains [1] and for in-line optical gating and optical demultiplexing [2].

Such applications, however, require that the modulator be insensitive to polarisation because optical polarisation control is very difficult in transmission lines. A modulator having a bulk material [3] has a low polarisation dependence in contrast to a modulator having a multiquantum well (MQW) structure [4] because electroabsorption due to the Franz-Keldysh effect is inherently insensitive to light polarisation. Another important way of accomplishing this is to decrease the differential between the optical confinement factors for TE and TM polarised light. This Letter focuses on an extremely low polarisation-dependent EA modulator we have developed combining a polyimide-buried high-mesa ridge structure with an InGaAsP bulk material as the absorption layer.

Device structure: The EA modulator has an InGaAsP bulk absorption layer (0.26μm thick) with a PL peak wavelength of 1.47μm and an undoped InP layer (0.1μm thick) to prevent Zn diffusion from the upper layer (Fig. 1). All layers were grown through single-step metalorganic vapour-phase epitaxy (MOVPE).

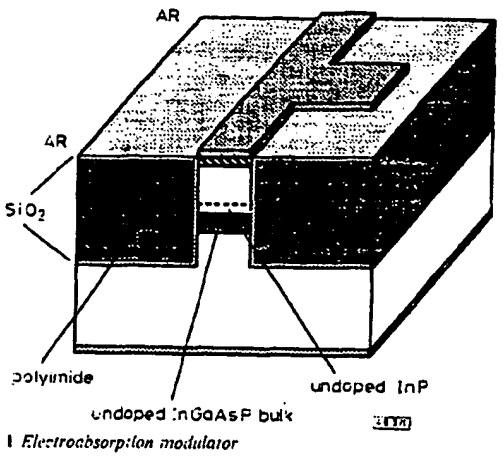

Fig. 1 *Electroabsorption modulator*

The high-mesa ridge structure, which is 3μm wide and 5μm deep, was formed by reactive ion etching. Both sides of the ridge waveguide were buried with polyimide to decrease the differential between the horizontal optical confinement factors of TE and TM polarised light. This structure also enables us to reduce the capacitance of the electrode pad.

The front and back facets were coated with antireflection (0.1%) film using SiO_x.

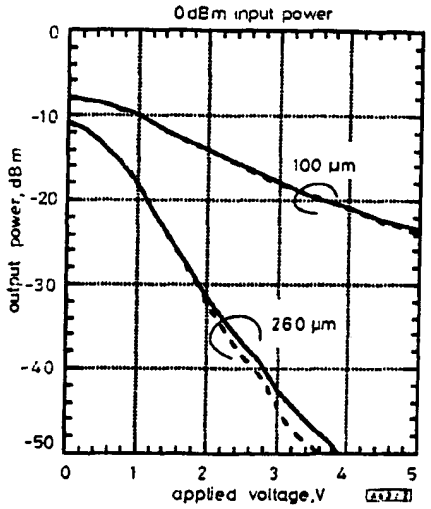

Fig. 2 *Output power against reverse voltage applied (V) for device lengths of 100 and 260μm*

—— TE polarised light
- - TM polarised light

Attenuation and polarisation dependency: In experiments at a 1.55μm wavelength with an optical input power of 0dBm for two different device lengths, 100 and 200μm, the extinction efficiency exceeded 10dB/V for the 260μm device (Fig. 2). The insertion losses measured using tapered fibre with a curvature of 10μm were ~8dB for the 100μm device and 11dB for the 260μm device. The propagation loss was 2dB/100μm and the estimated coupling loss per facet was ~3dB, almost independent of the input light wavelength. By using aspherical lenses for optical coupling, however, we obtained an insertion loss less than 9dB for the 260μm device.

The maximum polarisation dependence loss (PDL) for the 100μm device was 0.2dB over the entire measured applied voltage range. For the 260μm device, the maximum PDL was less than 0.3 dB up to 20dB, which represents the best data reported to date, to our knowledge, and possibly sufficient for practical application.

The PDL for a modulator with a bulk absorption layer is expressed simply as

$$PDL\,[\mathrm{dB}] = 20\log(\eta_{TM}/\eta_{TE}) + 4.343\{\Delta\Gamma L(\alpha_0 + \alpha(V))\} \quad (1)$$

where η_{TE} and η_{TM} are the coupling efficiencies per facet for TE and TM polarised light. $\Delta\Gamma$ is the differential between the optical confinement factors for the TE and TM modes, L is the device length, α_0 is the absorption coefficient at a zero field, and $\alpha(V)$ is the increase in the absorption coefficient due to the increase in the reverse applied voltage. Applying our measured PDL to the equation, $\Delta\Gamma$ is estimated to be of the order of 10^{-3}. This small $\Delta\Gamma$ may be due to the introduction of the polyimide-buried high-mesa ridge structure and a bulk absorption layer.

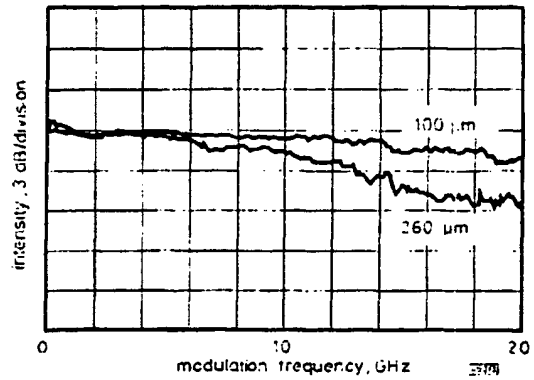

Fig. 3 *Small-signal frequency responses for device lengths of 100 and 260μm, and α-parameter against reverse applied voltage for several wavelengths of incident light for device length of 260μm*

High-speed, low-chirp characteristics: The device was installed on a strip-line header with a 50Ω terminator which was loaded parallel to the modulator, and a small-signal frequency response of 13 GHz was obtained for the 260μm device and >20GHz for the 100 μm device at a 3dB bandwidth (Fig. 3). The value for the α-parameter against reverse applied voltage is shown in Fig. 4. Values of the α-parameter were estimated for several wavelengths of incident light in the 260μm device by using an interferometry method [5] (Fig. 4). At a reverse voltage of -1V and 1.55μm wavelength, the α-parameter was 0.28 and depended strongly on the reverse applied voltage. The change in the α-parameter with reverse voltage, however, is smaller than that when using an MQW structure [6].

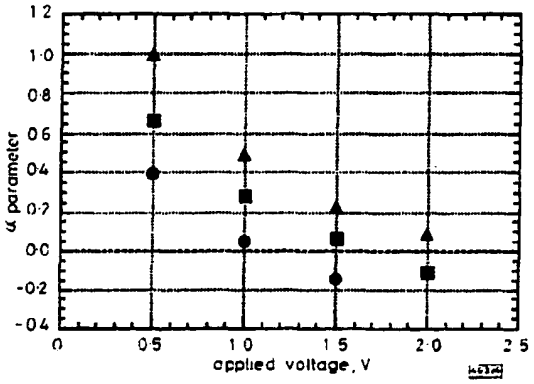

Fig. 4 *α-parameter estimated for several wavelengths of incident light*

Conclusion: We have achieved an extremely low polarisation dependence in an EA modulator by combining a high-mesa ridge structure buried with polyimide and InGaAsP bulk for the absorption layer. The polarisation-dependent loss was less than 0.3dB with an extinction ratio of 20dB. The high-frequency bandwidth was 13GHz and the low α-parameter was 0.28, which could satisfy the practical requirements for every high-bit-rate optical transmission system.

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Graphical analysis of contact resistance

M.G. Adlerstein

Indexing terms: Contact resistance

Low contact resistance is a recognised advantage for high-performance semiconductor devices. This translates to requirements for semiconductor layers with low sheet resistivity and metallisations with low specific contact resistance. In the Letter we present a graphical interpretation of the importance of these requirements and illustrate the analysis for various semiconductor materials.

Contact resistance analysis: Low contact resistance in semiconductor devices is a recognised requirement for optimum performance. Excessive resistance increases the charging time of semiconductor layers and reduces gain. It also results in excess dissipated power at both the input and output of devices. Typically, the net resistance of a horizontal contact is a function of both the metal/semiconductor interface as well as the thickness and conductivity of the semiconductor layer beneath the metal contact.

The modelling of contact resistance has been well established in the literature, and one approach is reviewed by Shur [1]. However, one can interpret the situation with different boundary conditions and in a graphical format which gives insight into the contributing factors. Horizontal contacts are modelled as shown schematically in Fig. 1. The resistor network models the distributed current flow in the structure. The metal contact resistance is represented by a network of parallel resistors (each with a value R_c) feeding a string of series resistors (each with a value R_s) which model the horizontal flow through the semiconductor layer. A network where the density of resistors tends toward infinity represents continuous material layers. The value of the resistors can be defined in terms

respectively. These losses are relatively low compared to those of Si IID waveguides (~40dB cm^{-1} [3]). In contrast, a loss of about 50cm^{-1} (~210dB cm^{-1}) has been calculated in the untreated lasers with 500 μm long passive waveguides.

Conclusion: Oxide stripe bandgap shifted lasers have been fabricated from the material intermixed to different degrees using a novel plasma intermixing technique. Results indicate that the material is still of high quality after intermixing.

Oxide stripe extended cavity lasers have been fabricated to demonstrate the use of the plasma technique in a photonic integrated circuit application. The results show that selective quantum-well intermixing helped to reduce the threshold current by a factor of 5. Losses as low as 18dB cm^{-1} have been measured in a laser with a 500μm-long extended cavity section intermixed using the plasma damage induced layer intermixing process.

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Highly efficient optical phase modulator in SOI waveguides

C.K. Tang and G.T. Reed

Indexing terms: Silicon-on-insulator, Optical waveguides, Phase modulation, Optical modulation

The realisation of a low-loss, highly efficient, singlemode optical phase modulator in SOI is reported. At a wavelength of 1.5 μm the figure of merit for the device, the induced phase shift per volt per millimetre, is greater than 200°/V/mm. To our knowledge, this is the highest reported value to date. In addition, the device drive current (< 10mA) is thought to be the lowest yet reported.

Introduction: Silicon is the backbone of the microelectronics industry, and its initial role in integrated optics as a substrate material is now changing to that of the guiding medium itself. Today silicon-based waveguides exhibit losses of well below 1 dB/cm (see, for example [1, 2]). Silicon technology is well established and relatively inexpensive. The potential of silicon electronic circuits integrated monolithically with silicon guided-wave devices has generated much interest in developing low-cost silicon-based integrated optical devices.

Optical waveguides, bends, r-junctions [3], optical switches and modulators [4 – 7] in silicon have received much attention in recent years. In this Letter we describe the characteristics of an optical phase modulator fabricated in SIMOX material (separation by implantation of oxygen).

Electric fields, free carriers and the thermo-optic effect provide potential mechanisms for modulation of the refractive index (and therefore phase) in silicon. In 1987 Soref and Bennett studied the refractive index change in silicon [8] due to the Franz-Keldesh effect, the Kerr effect and charge carrier effect. They concluded that for experimentally reasonable values of applied field and injected carriers the changes in refractive index were at least two orders of magnitude larger for the latter.

Integrated electro-optic switches in silicon reported to date have been based on rib waveguides in epitaxial silicon [6] and SOI waveguides [7]. The former have suffered from relatively high waveguide losses, and many of both types have required relatively high current densities as well as high switching currents [6] of the order of 1×10^4A/cm^2 and (200 – 800mA), respectively. This has led to the thermo-optic effect (TOE) [9] competing with the free-carrier effect to change refractive index in opposing senses, and consequently has resulted in inefficient devices. Singlemode TOE switches/modulators have also been realised [9], although the high power requirements (~245mW) may limit the practical use of such devices.

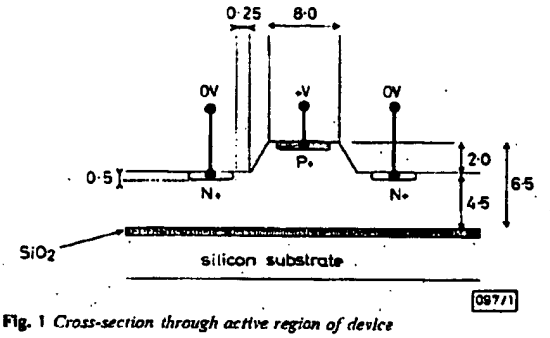

Fig. 1 *Cross-section through active region of device*

All dimensions in μm

In this Letter we describe the characteristics of an elongated *pin* diode embedded in a singlemode optical waveguide. Fig. 1 shows the cross-section through the active region of the device. The operating principle of the modulator is as follows: application of a forward bias injects carriers into the central waveguiding area, thus altering the local refractive index and therefore the phase of a propagating optical wave. MEDICI, a two-dimensional semiconductor simulation program, was employed to optimise the overlap of the injected carrier profile and the fundamental optical mode profile and therefore the phase change of the optical wave for a given applied voltage [10]. This was achieved by optimising the device geometry.

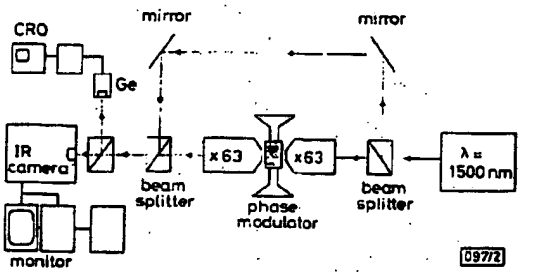

Fig. 2 *Schematic diagram of Mach-Zehnder interferometer used to measure phase change*

The modulator was incorporated into one arm of a free-space Mach-Zehnder (M-Z) interferometer as shown in Fig. 2. Light passing in one arm of the interferometer may be subjected to a phase shift if the necessary voltage is applied to the *pin* diode modulator on that arm of the Mach-Zehnder interferometer. The interference between the two arms produces a series of fringes at the output arm of the M-Z. We can determine the required voltage V_π to produce a π phase shift by observing the phase shift in the fringes as the applied voltage is increased. Modulation of the

output is thus achieved by a voltage-controlled phase shift in one arm of the M-Z interferometer.

Results: KOH etching along the (1,1,1) plane was used to produce smooth sidewalls and therefore low scattering losses. The measurement losses of the realised waveguide were lower than 1dB/cm. The device had the dimensions shown in Fig. 1 and had an interaction length of 500μm, and the waveguides were singlemode and had multi-micrometre dimensions, supporting the work of Soref *et al.* [11].

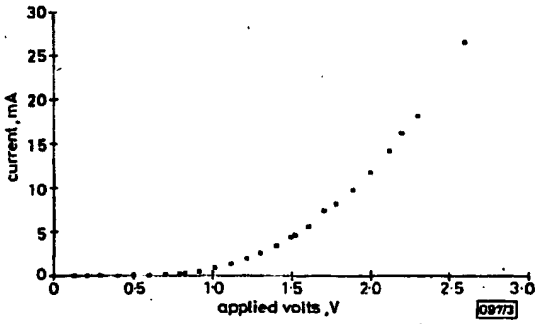

Fig. 3 *Forward characteristic of silicon pin diode modulator*

The forward characteristics of the device are shown in Fig. 3. The electrical characteristic is, as expected, that of a silicon diode.

Observation of a π phase shift in the fringes occurred for an applied forward bias of V_π = 1.7V. The current flowing through the phase modulator at this applied voltage was recorded as I_{mod} = 7mA.

A figure of merit η can be defined as the induced phase shift per volt per mm,

$$\eta = \pi / V_\pi L_\pi = 212^\circ \text{ /V/mm}$$

where L_π is the interaction length of the modulator for a π phase shift in millimetres (= 0.5mm).

Assuming that the current flows through the rib, we can approximate the junction area as $A = wL$, and so current density J = 175A/cm², where w is the waveguide width and $L = L_\pi$.

The current density of the device is approximately an order of magnitude lower when compared to previously reported devices in silicon [6, 7]. A limitation of the modulators in silicon to date has been the relatively large power requirement which has led to the TOE playing a very significant role [4]. Taking a 1-dimensional simplified treatment of heat transfer and assuming negligible heat losses from convection and radiation losses and no lateral diffusion of heat energy, we can approximate the heat transport from the heater to the silicon as

$$P = VI = \Delta T w L / (t_{si}/k_{si}) = 11.9 \text{ mW}$$

where t_{si} is the thickness of the silicon layer and k_{si} is the thermal conductivity of silicon. We find $\Delta T \simeq 0.138$K. Because silicon exhibits a refractive index change due to temperature, Δn_{tm}, of 1.86 × 10⁻⁴K⁻¹, the ratio of the refractive index change due to free carrier effect and that due to the thermo-optic effect can be expressed as $\Delta n_{fc}/\Delta n_{tm} \simeq 58$. So for this device the thermo-optic effect is negligible.

Conclusion: We have realised a highly efficient, singlemode, low-loss, multi-micrometre silicon *pin*-diode modulator, which has very low operating power requirements. The thermo-optic effect has been shown to be negligible.

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InGaAsP/InP strained MQW laser with integrated mode size converter using the shadow masked growth technique

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Indexing terms: Integrated optics, Optical couplers, Semiconductor junction lasers, Semiconductor quantum wells

The authors report the realisation of a planar buried-heterostructure (PBH) strained multiquantum-well (MQW) laser emitting at 1.52μm with integrated vertical taper using the shadow masked growth (SMG) technique. The threshold current is 8mA and the coupling loss to a cleaved singlemode fibre is only 3.3dB.

Introduction: In optical communication systems several optical interconnections between semiconductor optoelectronic devices and singlemode fibres are required. The very small refractive index difference in a glass fibre results in a weakly guided optical mode with a typical mode size of 8 – 10km for 1.55μm wavelength. Because the mode size in an optoelectronic waveguide device is much smaller (< 2μm) and generally highly asymmetric, there is large mode mismatch between the fibre mode and the device mode, and therefore the fibre-chip coupling efficiency is low.

During the past few years, many researchers have focused on the integration of mode size converters with optoelectronic waveguide components, to achieve a larger and more symmetric near-field pattern at the device facet ([1] and references therein). Such components allow low coupling losses and large alignment tolerances and hence lower packaging costs.

We have previously demonstrated the monolithic integration of a mode size converter with a PBH InGaAsP/InP double-heterostructure laser using the SMG technique, which exhibited a coupling loss as low as 4.8dB to a cleaved singlemode fibre [2]. In this Letter we present a PBH InGaAsP/InP strained MQW laser with integrated mode size transformer and a coupling loss of 3.3dB.